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Trade-off between water loss and water infrastructure quality: A cost minimization approach

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Abstract

In this paper, we focus on the issue of water loss caused by leakage from obsolete water mains. We develop in this theoretical paper, a cost minimization problem of a water utility that faces leakage from water mains. Our framework enables us to determine the optimal water main quality index according to different parameters such as the cost of water production, the quantity demanded and the cost of installing good quality water mains.

Key words: Water Loss, Infrastructure Quality, Cost Minimization.

Code JEL: D24, Q21, Q25.

1 Introduction

Lack of investment in water main leakage reduction is a major issue around the world. Regardless of the ownership type of the water utilities (public or private) replacement of outdated mains have been neglected as it is heavily costly. In the U.S. "for decades, these systems - some built around the time of the Civil War - have been ignored by politicians

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and residents accustomed to paying almost nothing for water delivery"[1]. Over the next two decades the renewal needs in the U.S. amount to at least 1 trillion dollars (AWWA, 2012). Similarly, France also faces investment needs that are largely unmet. Their renewal needs amount to 1.5 billion euros per year while they currently invest barely 800 million euros -satisfying only half the requirement (Salvetti, 2013). According to OFWAT calculations, in Britain, it would cost 250 billion euros to rebuild the entire infrastructure in one shot. Although the financial requirements are burdensome, once rebuilt, the mains would have an economic life of 50 to 100 years (Barraqué, 2009). Clearly, the issue of water main replacement embeds the trade-off of short-run and long-run costs. In light of political popularity, governments engage less in costly actions that might lead to increased water prices in the short run while future generations reap the benefits. Therefore, naturally investments will be "biased towards shorter-term gains" (Spiller and Savedoff, 1999). In France, a form of incentive mechanism has been put in place - "The French Decree published in January 2012, sets a specific level of network efficiency rate which all water services should reach by 2015" (Salvetti, 2013). In other words, it enforces a rate of water loss of 15% for urban regions and 20% for rural regions. Those who do not comply to this Decree by the deadline, will be faced with heavy taxes; which further stresses the incentive to reduce water loss today. Moreover, the Water Framework Directive (WFD) put forward by the European Union in 2000 urges all member states to implement the principle of full cost recovery of the costs incurred by water utilities (Elnaboulsi, 2009). Such a measure is intended for water utilities to be able to cover their costs of investment in replacing obsolete water mains.

The existence of water loss has various repercussions; economic and financial impacts along with health and hygiene. Economically speaking, water that is lost through poorly maintained mains are extractions of water resources that is directly put to waste, aggravating water scarcity. In financial terms, water loss is the amount of water that is not serviced to the consumer; hence a loss of potential revenue. Although in many cases the agencies overcharge the consumers to compensate for the leaks which leads to

[1] *The New York Times* 2010.

a dead-weight loss. Moreover, "leaky pipes are known for increasing pumping energy [...] and can increase the risk of compromised water quality by allowing intrusion of polluted groundwater" (Colombo and Karney, 2002). The increase in cost due to increasing water input into the service network is the "marginal cost associated with drilling, consisting mostly of energy and treatment cost" (Garcia and Thomas, 2001). This wasted energy has further consequences on the environment associated with the emission of CO2 and greenhouse gases due to energy production and consumption.

In most developed countries, water main leakage is the main component of water loss. In Europe, water loss ranges from 9 to 30% and in the U.S. about 16% of clean drinking water is wasted everyday (EPA, 2013). The thought naturally occurs to implement an initiative to reduce leakage; however, most of the water infrastructure around the world are outdated for its service potential. The reason is because replacement of mains in highly dense cities is a huge burden to the water utilities in terms of costs. For instance, in the U.S. the price paid by consumers are heavily underpriced which creates difficulty for water utilities to cover their cost of production. Many studies have covered issues of cost efficiency of water utilities, especially with relation to ownership type (public, private or public-private-partnerships) and pricing policies. Very few mentioned the effect of water loss on the cost of water utilities. Moreover, the empirical studies on ownership type have conflicting results and are not conclusive. Most likely due to the inherited structure of the water utility being a Natural Monopoly, where no incentive for efficiency exists, preventing competition.

Our contribution to the literature is to create a theoretical model that underlines the necessity of leakage reduction which not only alleviates the stress on water resources but also contributes to the cost efficiency of the water utility. Regardless whether the utility is managed by the public, private or public private partnership, we develop a general cost minimization problem that could be applied to any ownership type; as according to the literature, it does not represent striking differences. Here, as a first step to a theoretical framework, we introduce a static cost minimization model that illustrates the benefit of the utility to maintain a good level of water main infrastructure. In other words, we focus on the quality level of water mains as a tool to give recommendations on the need for main replacement. A high proportion of good quality water mains reflects the situation where a large quantity of obsolete mains are replaced. By incorporating water loss as a constraint to the supply of water faced by a given demand, we show that raising the level of water main quality is optimal. In other words, the proportion of the total water main network should consist of mains that are younger than 50 years of age.

Finding the optimal level of quality is challenging due to the different cost structures of water utilities. In our model we simplify the cost structure by focusing on the cost of water extraction (pumping and treatment costs) and the cost associated to the quantity of good quality water mains. The tradeoff between maintaining good quality water mains and pumping more water to compensate for water loss depends on their relative cost. We simulate the model with the data of American and French water agencies. We show that the theoretical index we find is not far from the current one observed in France but definitely higher than the one in the US. We highlight heterogeneity issues when proceeding to simulations for different water agencies in France and in the US. We show that the theoretical index is not far from the current ratio observed in France but significantly higher for the United States. Moreover we highlight heterogeneity issues when proceeding with simulations of different water utilities.

The paper is divided into five sections. In the second section, we present the literature review, in the third section we present the model, in the fourth section we present the data and results from the simulation and in the fifth section we conclude.

2 Literature Review

Most empirical studies dealing with water services focus on the effect of ownership type and cost efficiency, performance assessments based on benchmarking techniques, the degree of economies of scale and scope of the utilities and optimal pricing models. Moreover, studies on the effect of water utility ownership type (public, private or public-private partnership (PPP)) on performance dominates the literature. The issue of water loss has seldom appeared in the literature as the primal focus of a study. Among the literature that covers the issue of water loss, only few are based on a theoretical approach. For example, Pearson and Trow (2005) estimate "economic levels of leakage". In short they conclude that if producing water is less costly than investing in activities that reduce leakage, water utilities should produce more water (extract water) to compensate the amount of water lost through leaks. The marginal cost of water is estimated by the difference in cost of producing one more unit of water in terms of power (energy), chemicals (for treatment) and labor.

Another example is the theoretical paper applying contract theory to public water utility regulation by Garcia and Thomas (2003). They examine the impact of asymmetric information on the production decision of regulated public water utilities. The asymmetry of information depicts the uncertainty of the delegated utility's decision whether or not to exert effort in reducing water loss in favour of water network quality improvement. The solution of their model shows that due to asymmetric information between the local community and the water utility, information rents increase with reduction in water loss. Hence in the optimal contract, "the principal requires the operator not to reduce losses". This result adds to the intuitive hypothesis of the likelihood that water loss reduction may be suboptimal if the cost of reduction exceeds the benefit.

Moreover, a recent theoretical approach on the analysis of water infrastructure has been developed by Hansen (2009). He tested the effects of population, capital and policy on the decision of optimal water utility infrastructure investment. He sets up a dynamic optimization problem constrained by capital depreciation. The empirics proved the theoretical model relevant; however, the approach of profit maximization using a Cobb-Douglas production function with inputs Capital, Labor and Infrastructure Investment appears over generalized and not suitable to the characteristics of a water utility.

Water loss appears often in empirical papers that assess the performance of the water utilities according to various factors such as ownership type and regional characteristics. For example the study by Chong et al. (2006), do not find evidence that the level of leakage, among the quality variables, has a significant affect on the "performance" variable estimated by prices. However, another study by Salvetti (2013), infers that "groups of water services complying with the French leakage regulation show a higher water price than the group of services failing to match the regulation". She reasons by the fact that utilities abiding by the regulation set by authorities, tend to charge higher prices to customers. This evidence strongly supports our hypothesis of the water service's lack of investment in quality improvement of their infrastructure due to the burden born by the customers via higher prices. However, the price of water paid by customers may not be a global indicator of how effectively the water utilities are managed since these water rates are heavily regulated and is a problematic measure to represent the true cost of the servicing firm.

Garcia and Thomas (2001) compare the marginal cost of labor applied to the infrastructure replacement (as most replacements are highly labor-intensive) and the marginal cost of pumping water (which consists mainly of energy costs) to decide whether or not to invest in leakage reduction. However by taking the "short-run" marginal cost of main replacement, it is evident that it will be much greater than the "short-run" marginal cost of pumping water to satisfy customer demand, since the long-run costs to society are ignored. Thus, they conclude that a "joint production" of water loss and service output has a cost advantage; hence reasoning by the concept of economies of scope.

In line with the study by Garcia and Thomas (2001), Martins et al. (2012) estimates an empirical cost function in a similar manner with two outputs; water loss (y^l) and service output (y^s) to observe the effect of reducing water losses on the water utility performance in terms of cost effectiveness. They compare the cost of producing water loss and the cost of producing serviced water. The conclusion is that "the marginal cost of y^l is greater than the marginal cost of y^s". This can be viewed as an incentive for reducing water loss; it would be cost effective for the utility to produce without water losses.

Zschille and Walter (2010) infer from their empirical work on assessing the cost efficiency of the German water utilities, that "water losses and elevation differences in a service area turn out to be significant cost driver"; however, "incentives to reduce costs and corresponding prices are still missing in Germany so that there is no need for water utilities to supply water in an efficient way." The coefficient that measures the increase in cost of water loss appears significant.

As we can see, there have been several empirical studies applied to different countries that highlight the issue of water loss, however a theoretical model illustrating the effect of water loss on the cost of the water utility has never been presented in the literature. Our principle focus is to portray theoretically and simulate the optimal trade-off between water loss and water infrastructure quality for a cost minimizing water agency.

3 The Water utility's decision

Consider a cost-minimizing water utility that provides potable water to households. Regardless of ownership type, the utility will behave in a cost minimizing way. The cost of the utility depends on water input $\left(W^{in}\right)$ with its associated cost (ρ), good quality mains $\left(\overline{K}\right)$ with its associated cost (r), bad quality mains $(\underline{K})$ with its associated cost (m) and fixed costs (FC). The water main network is fixed at (K) which is a sum of good quality mains $\left(\overline{K}\right)$ and bad quality mains $(\underline{K})$. Good quality mains are defined as mains that are "young", in service for less than 50 years and the obsolete or bad quality mains are those that have surpassed their useful life (older than 50 years) (Majdouba, 2011). The utility is faced with a constraint to minimize water loss. Water loss, $\left(W^{l}\right)$, is determined by a linear function that depends on $\overline{K}$, reflecting the concept of the iceberg cost. It is denoted as $\alpha\left(\overline{K}\right)$ multiplied by the quantity of water input, $\left(W^{in}\right)$. $\alpha\left(\overline{K}\right)$ takes on values from 0 to 1 without ever reaching 1 in order to maintain a positive quantity of water supplied to the consumers. The water loss function then is:

$$W^{l} = \alpha\left(\overline{K}\right) W^{in}, \tag{1}$$

where $\alpha'_{\overline{K}} \leq 0$ and $\alpha''_{\overline{K}} \geq 0$. In other words, the lower the quality of the mains, $\alpha\left(\overline{K}\right)$ will be closer to one; hence greater the water loss.

Along with the water loss constraint, the utility faces a demand that must be satisfied. i.e. the output constraint. The production of potable water is a very particular process in which the input (water) is transported (after treatment) through water mains and arrives to the households in the form of tap water. Therefore, instead of applying a production function that converts inputs such as capital and labor into the output of water, we define the supply of potable water as the difference between the amount of water extracted $\left(W^{in}\right)$ and the amount of water lost through leakage due to bad quality mains $\left(W^{l}\right)$. This total amount supplied must meet the required demand denoted as $q\left(p\left(\overline{K}\right)\right)$. In our model, the quantity demanded is a function of the quality of water mains. The better the quality, the higher the price of water charged to consumers; hence, the lower the quantity demanded. In other words, $p^{'}_{\overline{K}} \geqslant 0$ and $p^{''}_{\overline{K}} \leqslant 0$ (AWWA, 2012), $q^{\prime}_{p} \leqslant 0$ and $q^{\prime\prime}_{p} \geqslant 0$, therefore $q^{\prime}_{\overline{K}} \leqslant 0$ and $q^{\prime\prime}_{\overline{K}} \geqslant 0$. Since all water utilities are subject to certain regulations that assure the right to water to all citizens and impose a cap on price charged to consumers; a profit maximisation model is not appropriate. Moreover, as indicated in the empirical study of the cost structure of a private versus public water delivery service by Feigenbaum and Teeples (1983), "when level of output and factor prices are exogenously determined, it is preferable to estimate firm cost functions instead of production functions." Hence, subject to duality conditions, we use a cost minimisation approach instead of a profit maximisation approach.

In our model, we also identify the situation where quantity demanded is exogenous, denoted by $(\overline{q})$; in other words, the price charged to consumers do not reflect the cost of good quality water mains. Such a scenario is quite relevant today; as reported in the European Water Framework Directive, the price of water barely covers the full supply cost. The supply cost consists of capital charges and O&M costs; while the full cost will entail in addition the supply cost, the full economic cost (Economic externalities and Opportunity cost) plus the environmental externalities (Rogers et al., 1998). Data published on the IBNET (The International Benchmarking Network for Water and Sanitation Utilities) show the average operating cost coverage ratio by different regions in the world. For example, in Europe and central Asia, revenues from customers cover mainly the operating and maintenance cost; clearly representing a fraction of the full cost associated to water service delivery.

The water utility's decision is as follows:

$$\min_{\overline{K}} \quad \rho W^{in} + r\overline{K} + m\underline{K} + FC \tag{2}$$

$$\text{subject to:} \quad W^{in} - W^{l} \geqslant q\left(p\left(\overline{K}\right)\right) \tag{3}$$

$$W^{l} = \alpha\left(\overline{K}\right) W^{in} \tag{4}$$

$$\overline{K} + \underline{K} = K \tag{5}$$

$$W^{in} > 0 \tag{6}$$

$$\overline{K}, \underline{K}, W^{l} \geqslant 0 \tag{7}$$

$$0 \leq \alpha\left(\overline{K}\right) < 1 \tag{8}$$

$$\tag{9}$$

After substituting the constraints into the objective function we obtain the following expression for the cost denoted by $C\left(\overline{K}\right)$:

$$C\left(\overline{K}\right) = \frac{\rho q\left(\overline{K}\right)}{\left(1 - \alpha\left(\overline{K}\right)\right)} + (r - m)\overline{K} + FC$$

For simplicity we replace $q\left(p\left(\overline{K}\right)\right)$ by $q\left(\overline{K}\right)$ from here on.

After deriving with respect to the variable $\overline{K}$ we obtain the following first order condition:

$$\frac{\partial C}{\partial \overline{K}} = \frac{\rho q'_{\overline{K}}}{\left(1 - \alpha\left(\overline{K}\right)\right)} + \frac{\rho q\left(\overline{K}\right) \alpha'_{\overline{K}}}{\left(1 - \alpha\left(\overline{K}\right)\right)^2} + (r - m)$$

where the first two terms are negative. When r tends to zero or ρ is very large the first derivative can be negative for any values of $\bar{K} \in [0, K]$. This implies that when the cost of good quality mains is very low or when the cost of water input is very high, the optimal level of $\bar{K}$ is K. In other words, the entire main network should consist of only good quality mains. Conversely, when the cost of water input is very low, the first derivate may be positive for any $\bar{K} \in [0, K]$ implying that it is not optimal to have good quality mains. When an interior solution exists, the optimal proportion of good quality mains is the solution to $\frac{\partial C}{\partial \overline{K}} = 0$. The following second order condition confirms that the optimal quantity of $\overline{K}$ indeed minimizes costs.

$$\frac{\partial^2 C}{\partial \overline{K}^2} = \frac{\rho q''_{\overline{K}}}{\left(1 - \alpha\left(\overline{K}\right)\right)} + \frac{2\rho q'_{\overline{k}} \alpha'_{\overline{K}}}{\left(1 - \alpha\left(\overline{K}\right)\right)^2} + \frac{2\rho q\left(\overline{K}\right)\left(\alpha'_{\overline{K}}\right)^2}{\left(1 - \alpha\left(\overline{K}\right)\right)^3} \geqslant 0$$

The implicit form of the optimal solution is given as follows:

$$\frac{q\left(\overline{K}\right)\alpha'_{\overline{K}}}{\left(1 - \alpha\left(\overline{K}\right)\right)^2} + \frac{q'_{\overline{K}}}{\left(1 - \alpha\left(\overline{K}\right)\right)} = -\frac{(r - m)}{\rho}$$

In the case where quantity demanded is exogenous (i.e. $q'_{\overline{K}} = 0$), the optimal solution is given as follows:

$$\frac{\overline{q}\alpha'_{\overline{K}}}{\left(1 - \alpha\left(\overline{K}\right)\right)^2} = -\frac{(r - m)}{\rho}$$

The comparative static analysis gives the following results: [2]

- When quantity demanded changes exogenously: $\frac{d\overline{K}_0}{d\overline{q}} \geq 0$ and $\frac{dW_0^l}{d\overline{q}} \leq 0$
- When the cost of water input increases: $\frac{d\overline{K}}{d\rho} \geq 0$ and $\frac{dW^l}{d\rho} \leq 0$
- When the cost of good quality mains increases: $\frac{d\overline{K}}{dr} \leq 0$ and $\frac{dW^l}{dr} \geq 0$

The subscript "0" indicates the case when quantity demanded is exogenous; i.e. $q'_{\overline{K}} = 0$. If exogenous quantity demanded increases, the above comparative static suggests that the proportion of good quality mains should increase which implies a reduction in water loss. Moreover if the cost of water input increases (due to an increase in energy cost, the degree of water scarcity), the proportion of good quality mains should increase; hence reducing water loss. Finally, the greater the cost of good quality mains,

[2] The expression of the derivatives are given in the Appendix 1.

the greater the water loss since the proportion of bad quality mains will be large. This will increase the amount of water pumped into the system to maintain the supply of water to consumers.

4 Simulation

4.1 Explicit functions of the model

In order to conduct simulations, in this section we define the different functions of the model.

We define the quantity demanded as a function that depends on the price of water charged to consumers:

$$q(p) = \frac{q_0}{p\left(\overline{K}\right)^{\theta}}$$

where q_0 is the annual average quantity demanded by households based on current level of consumption and θ is the price elasticity. We refer to q_0 as unconstrained demand. $p\left(\overline{K}\right)$ is the price function that depends on the quantity of good quality mains :

$$p\left(\overline{K}\right) = \left(\frac{(r-m)\overline{K}}{q_0}\right)\beta + \overline{p}$$

where $1 \geq \beta > 0$ represents the proportion of the cost of good quality mains that is reflected on the price of water charged to consumers. We consider this as the ”political parameter” which imposes the cost recovery initiative on water utilities. The closer β is to 0, the smaller the effect of main quality cost on the price. When there is zero cost recovery, $p\left(\overline{K}\right) = \overline{p}$, which we assume as the price charged to consumers today. $\beta = 1$ is the maximum degree of cost recovery possible. We denote it as the ”full cost recovery”.

Combining the two functions, we define quantity demanded as a function of $\overline{K}$.

$$q\left(\overline{K}\right) = \frac{q_0}{\left(\left(\frac{(r-m)\overline{K}}{q_0}\right)\beta + \overline{p}\right)^{\theta}}$$

When $\beta = 0$ the quantity demanded does not depend on the good quality mains; hence the demand is fixed and it is defined as:

$$\overline{q} = \frac{q_0}{\overline{p}^{\theta}} \tag{10}$$

where price is exogenous and does not reflect the cost of good quality mains.

We define the Iceberg function as follows:

$$\alpha\left(\overline{K}\right) = \alpha_0\left(1 - \frac{\overline{K}}{K}\right)$$

When the entire water infrastructure network is composed of good quality mains $\alpha\left(\overline{K}\right) = 0$; i.e. no water loss since $W^l = \alpha\left(\overline{K}\right)W^{in}$. When the entire network consists of bad quality mains $\overline{K} = 0$, $\alpha(0) = \alpha_0$, the critical rate of water loss.

Given these functions, we conducted a simulation in order to obtain the optimal water main quality ratio $\left(\frac{\overline{K}}{K}\right)$, which we refer to as the **optimal water main quality index** in percentage form. The aim is to compare the theoretical index and the current index observed in France and in the U.S.. We have selected three water agencies from France and four water utilities from the U.S. in order to observe the effect of geographical and population heterogeneities on the optimal water main quality index.

Moreover we simulated the impact of several key parameters; the political parameter of cost recovery (β), the cost of water input (ρ) and the cost of good quality mains (r). These results will help shed light on the different forces that affect the optimal quality of water mains.

4.2 Calibration

We have compiled data from large databases such as the United States Environmental Protection Agency (EPA), the American Water Works Association (AWWA), Observatoire national des services d'eau et d'assainissement (SISPEA), and Office National de l'Eau et des Milieux Aquatiques (ONEMA).

We collected data on the following parameters; $\alpha_0, r, \rho, q_0, \overline{p}$ and K. We assume the maintenance cost to be $m = 0$ in our model since for the available data, the value was negligible; hence, we may conclude that its impact on the results is minimal. Theoretically the presence of m will reduce the cost of good quality mains which would drive up the optimal quantity of good quality mains and raise the optimal water main quality index. θ was obtained by the results from empirical studies (Arbués et al., 2003) and β is the political parameter reflecting the degree of cost recovery which we manipulate to observe its impact on the quality index. ρ is the cost of pumping and treating a m^3 of water. In France, since the full coverage of the cost of water production is enforced, ρ represents 44.5% of the price of water paid by consumers (ONEMA, 2012). α_0 is the rate of water loss when the entire water main network consists of bad quality mains, which we refer to as the "critical rate of water loss". In France, around 60% of water mains are good quality mains and the associated current level of rate of water loss is 24% (Berland and Juery, 2001). Therefore, α_0 is 0.6.[3] On the other hand, in the U.S., there are around 80% good quality water mains and the associated rate of water loss is 16% (Folkman, 2012). Hence, α_0 is 0.8. In practice, the quality index depends not only on the age of the mains but also on their material (PVC, cast iron, etc.).

Moreover, q_0 was computed by multiplying the population by the average annual quantity of water required per person and r was computed by dividing the cost of new mains per kilometre of main length by the average year of amortisation, which is 50 years (Colbach, 2014).

The unit measures for the data are presented in Table 1.

[3] α_0 was computed by solving the equation $\alpha\left(\overline{K}\right) = \alpha_0\left(1 - \frac{\overline{K}}{K}\right)$. For France, we substituted 0.24 into $\alpha(\overline{K})$ and 0.6 into $\frac{\overline{K}}{K}$.

4.3 Results: Country average of the U.S. and France

First we simulated the model by fixing the parameters that reflect as close as possible the current average situation in France and in the U.S. However, simulating average values of a country could be misleading since the parameters depend on the characteristics of the region. For instance, the installation of new mains in an urban region costs almost four times more than in a rural region. Moreover, water input cost depends on the aridity of the region and the type of water resource used. Extraction of water from surface water is more costly than groundwater in terms of treatment costs. Hence comparisons of regional differences are more informative. Nevertheless, in order to capture and analyse the impact of the parameters on the quality index, as a starting point, we calibrated the parameters with average values and then conducted simulations by varying key parameters one at a time. Table 2 presents the calibration of the parameters and the optimal water main quality index for both U.S. and France. In both cases, we simulated with zero cost recovery ($\beta = 0$) which reflects the current situation today and implies a fixed quantity demand ($\overline{q}$). We observe that the optimal water main quality index for France is near its current value (61%) while for the U.S. we obtain 100% which is about 20% greater than their current quality index. We strongly emphasise that the value we obtain for the optimal water main quality index represents a **minimalist** scenario. In other words, the index leaves out the cost of maintenance, negative environmental and health externalities due to water leakage. If included, they could potentially drive up the quality index.

The optimal quality index is greater in the U.S. than in France due essentially to the differences in q_0, $\overline{p}$ and α_0. The consumption per capita of potable water is almost three times greater in the U.S. than in France; hence they are faced with a greater need to reduce water loss. Moreover, the price of water paid by consumers in the U.S. is less than half of the price in France. A low price leads to higher quantity demand which requires higher supply of water; hence a need for water loss reduction. Thirdly, the critical rate of water loss is greater in the U.S. than in France. This means, that

	Description	Units for France(U.S.)
α_0	Critical rate of water loss	[0,1)
K	Total main network distance	km
q_0	Unconstrained quantity demanded	m^3
ρ	Water input cost	€($) per m^3
$\overline{p}$	Current price of water	€($) per m^3
r	Cost of good quality mains	€($) per km
θ	Price elasticity of demand	[0,1]
β	Cost recovery	[0,1]

Table 1: Units defined for the United States and France

the replacement of bad quality water mains is more urgent for the U.S. than in France. Hence the three indicators point towards a higher water main quality index for the U.S.

Figure 1 shows the impact of the water input cost (ρ) and the cost of good quality water mains (r) on the quality index for France. The quality index for France increases from 0% to 100% for just a 2 € per m^3 increase in ρ. This result implies the sensitivity of the cost of water input. The scarcer the water resource becomes, the cost of extraction increases and the impact on the quality index becomes rapidly pronounced. On the other hand, the quality index for the U.S. remains 100% for all values of ρ. The optimal quality of the mains should be 100% good quality no matter the ρ for the U.S. to satisfy the large quantity demand.

On the other hand, the cost of good quality mains reduces the optimal water main quality index. A doubling of the cost of good quality mains reduces more than 50% the quality index. The cost of good quality mains depends on the geographic region of the country. A heavily urbanised city faces a larger cost of good quality mains than a rural region. Hence, an urbanised city facing a gradually rising scarcity of water is inclined to face a high optimal water main quality index.

The following four figures show the impact of the degree of cost recovery on the quality index, price level, rate of water loss and quantity demanded in France. In the left graph of Figure 2, we observe that the degree of cost recovery does not have much impact on the quality index. A shift from zero cost recovery ($\beta = 0$) to full cost recovery

	France(average)	US (average)
α_0	0.6	0.8
K	906,000	11,899,021
q_0	3,637,590,000	71,812,919,990
ρ	1.52	1.24
$\overline{p}$	3.39	1.32
r	4,890	6,058
θ	0.2	0.33
β	0	0
current $\frac{\overline{K}}{K}$ (%)	60	80
optimal $\frac{\overline{K}}{K}$ (%)	**61**	**100**
current $\alpha(\overline{K})(\%)$	24	16
optimal $\alpha(\overline{K})(\%)$	**23**	**0**
optimal financial loss	3.3 billion euros	0

Table 2: Calibration of parameters for the average of United States and France.

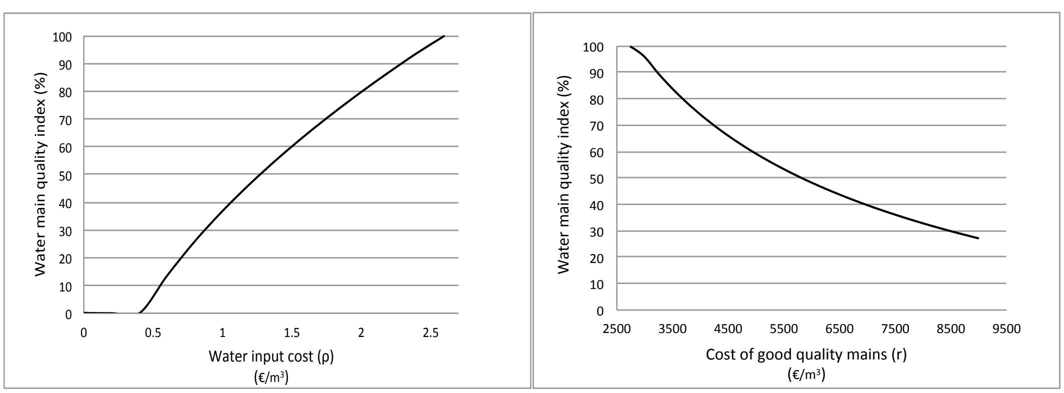

Figure 1: The impact of the **cost of water input**(ρ) and the **cost of good quality mains (r)** on the quality index for France

($\beta = 1$) only raises the index by 3%. This is because the cost recovery parameter has an overall impact that translates through two opposing paths. An increase in β raises the price and hence lowers quantity demand. A higher β incites the utility to raise the quality index; however, simultaneously a reduction in quantity demand reduces the need for good quality mains [4]. The right-hand side figure shows the impact of cost recovery on the level of water loss. The result is analogous to the reaction of the water main quality index. The reduction in water loss is a mere 1.2%.

Figure 3 shows that the price charged to consumers rises moderately with the rise in the degree of cost recovery; however, the right figure shows that the initial fall in quantity demanded is substantial. This implies that the impact of the cost recovery is felt the most as soon as $\beta \neq 0$. Any increase of β from the initial drop does not have much further impact on the reduction in quantity demanded since the corresponding substantial fall in $\overline{K}$ limits further reduction in demand.

The above results imply that *cost recovery* is a delicate issue. Depending on the initial conditions of the water utility, raising cost recovery could imply a delicate trade-off between water main quality and quantity demanded.

Nevertheless, Figure 4 shows that as β rises, the reduction in water loss leads to financial gain.[5] The overall gain from zero cost recovery to full cost recovery amounts to about 1.35 billion euros. Hence, although in terms of percentages the impact of cost recovery may seem negligible, it is significant in terms of financial value.

4.4 Results: regional differences within the U.S. and France

We now move to the analysis of regional differences in France and the U.S. In the case of France, we selected three different water agencies; namely Adour Garonne (A/G) in the South West, Seine-Normandie (S/N) in the North and Rhone-Mediterranee et Corse (R/M/C) in the South East. We chose these three agencies to represent the impact of

[4] See Appendix 2 for a mathematical proof

[5] The financial gain is calculated by computing the difference between the financial loss when $\beta = 0$ and when $\beta \neq 0$. The financial loss is calculated by multiplying the W^l by the price of water production (ρ).

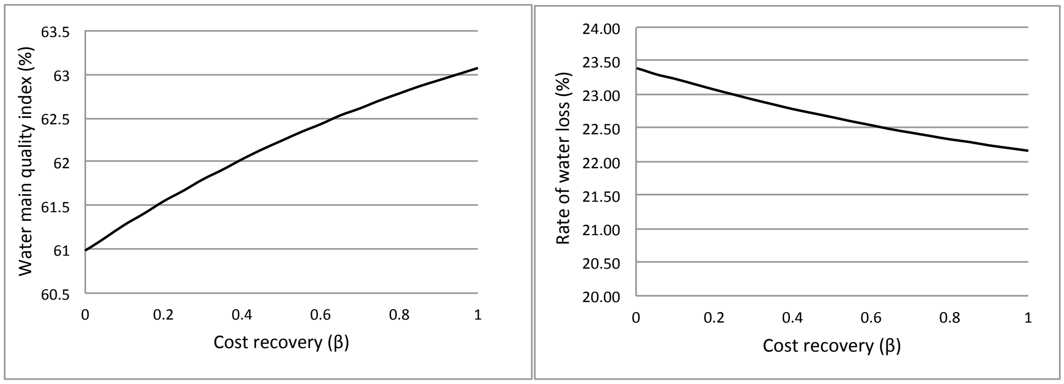

Figure 2: The impact of the **cost recovery initiative** (β) on the quality index and rate of water loss for France.

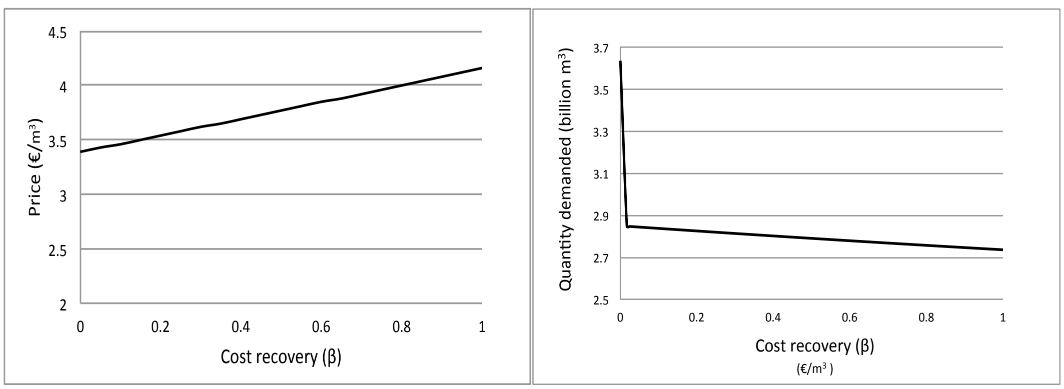

Figure 3: The impact of the **cost recovery initiative** (β) on the price of water charged to consumers and quantity demanded for France.

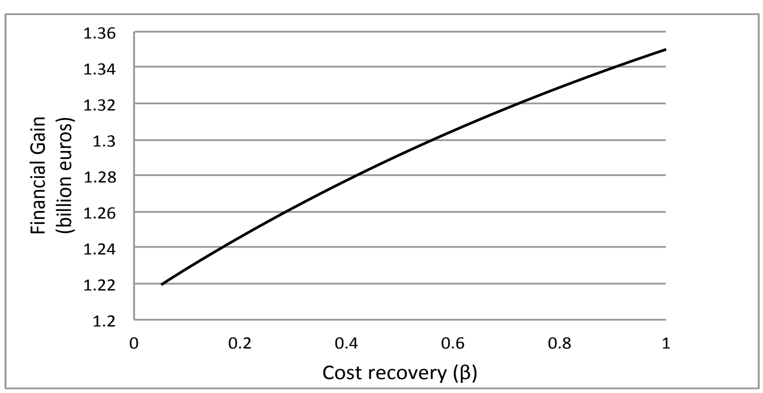

Figure 4: The impact of the **cost recovery initiative** (β) on financial gain for France.

	Adour Garonne	Seine-Normandie	Rhone/Med/Corse
α_0	0.6	0.6	0.6
K	209040	138403	168312
q_0	395,025,299	988,493,588	774,171,855
ρ	1.5	1.42	1.46
$\overline{p}$	3.75	3.85	3.25
r	3,900	4,800	4,800
θ	0.2	0.2	0.2
β	0	0	0
current $\frac{\overline{K}}{K}$ (%) [6]	55	76	53
optimal $\frac{\overline{K}}{K}$ (%)	**30**	**97**	**69**
current $\alpha(\overline{K})$(%)	27	14	28
optimal $\alpha(\overline{K})$(%)	**42**	**2**	**19**
optimal financial loss	1.2 billion euros	116 million euros	944 million euros

Table 3: Calibration of parameters for the different water agencies in France.

regional differences on the optimal water main quality index. For the U.S., we chose two counties from Wisconsin and two counties from California. Wisconsin is a state that has access to an abundant source of water while California is an arid region which relies mostly on imported water supply.

Table 3 shows the calibration of the three different water agencies in France and their optimal water main quality indices. We applied the average critical rate of water loss (α_0) of France since the installation of water mains are quite homogeneous around France. Moreover, we were able to compute the simulated current water main quality index by using the current rate of water loss associated to each agency and substituting the values into the iceberg function.

The quality index in Adour Garonne (A/G) is the smallest out of the three agencies essentially due to the quantity demand. Once again, we insist that the value of the optimal quality index represents the minimalist scenario; for instance, it leaves out the effect of negative environmental externalities. A/G is a highly rural geographic region; and the population is also small but more scattered compared to the other two regions. A smaller rural population implies a smaller quantity demand which diminishes the need to reduce water loss and a scattered population implies a larger total distance of water mains which raises the total cost to the agency. Both forces leads to a smaller quality index. On the other hand, as Seine Normandie (S/N) faces the largest quantity demand and the shortest distance of water main network, their quality index is the highest. In their case, the minimalist scenario is already near 100%; meaning with the given regional characteristics, almost the entirety of their water mains should consist of good quality mains. The characteristics of the region of Rhone Mediterranee Corse (RMC) fall between S/N and A/G; and hence their optimal water main quality index falls also in between. However, the current quality index and the rate of water loss show that the RMC agency in particular is performing sub-optimally. They are faced with a quantity demand almost the double of A/G; however, their current (simulated) quality index is less than A/G. Overall these results depict the significance of regional differences. Moreover, they give an indication of the likelihood of each agency attaining the recommended limit of the rate of water loss enforced under the Law of "Grenelle 2" of 2010: 15% for urban regions and 20% for rural regions (Radisson, 2011). Our results clearly show that a more urbanised region is more likely to reach a low level of water loss more than a rural region. A large reduction in water loss should be enforced in a highly urbanised region, such as Seine et Normandie while for a highly rural region, the limit should be less constrained.

Now we turn to the United States regional water utilities. Table 4 shows the calibrated values of the parameters and their optimal water main quality index. For α_0 we apply the average of the U.S. as a whole. The optimal water main quality index for the two utilities in Wisconsin (Madison and Milwaukee) is significantly smaller than the quality index for the two utilities in California (EBMUD and San Diego). The principal reason is the difference in water input cost (ρ). The water input cost in EBMUD and San Diego is at least 10 times greater than in Milwaukee and Madison. Therefore, with the given values, the reduction in water loss is far from a necessity in the utilities of Milwaukee and Madison. However, considering their current rate of water loss, 10% for Madison and 14% for Milwaukee, the simulated current water main quality index is

	Madison, WI	Milwaukee, WI	EBMUD, CA	San Diego, CA
α_0	0.8	0.8	0.8	0.8
K	1,368	3,154	6,759	5,314
q_0	33,552,421	115,682,086	242,469,500	270,465,000
ρ	0.066	0.06	0.66	0.75
$\overline{p}$	0.74	0.74	1.03	1.29
r	11,806	12,427	18,641	24,855
θ	0.33	0.33	0.33	0.33
β	0	0	0	0
current $\frac{\overline{K}}{K}$ (%) [7]	88	83	88	89
optimal $\frac{\overline{K}}{K}$ (%)	**19**	**24**	**100**	**100**
current $\alpha(\overline{K})$(%)	10	14	10	9
optimal $\alpha(\overline{K})$(%)	65	60	0	0
optimal financial loss	\$89 million	\$283 million	0	0

Table 4: Calibration of U.S. water utilities.

above 80%. It is almost four times the optimal quality index simulated by our model. In other words, given their level of ρ, there is very little need for reducing water loss. However, we must keep in mind that we are in the minimalist scenario. For instance, the quality index could be much higher if environmental externalities are taken into account.

On the other hand, the optimal quality index for EBMUD and San Diego is 100%. Again here, the water input cost plays a key role. Due to the aridity of the region, the water input cost is much greater than the utilities in the state of Wisconsin. Moreover, EBMUD and San Diego are both faced with a larger quantity demand; hence greater pressure on reducing water loss. This implies that regions faced with uncertainty of water availability are more likely to reflect the value of water on the cost of water input which leads to a higher optimal quality index.

5 Conclusion

In our paper, we developed a static cost minimisation problem of a water utility that faces water loss from leakage due to obsolete water mains. We conduct a numerical simulation on French water agencies and American water utilities to obtain their optimal water main quality index. Our optimal quality index illustrates the minimalist scenario in which negative environmental externalities and maintenance costs are left out. Hence the values we obtain is in fact the "minimum" optimal water main quality index that water utilities should achieve. In the case of France, we obtained a value quite close to their current quality index. However, the current average age of most of the water mains in France are over 40 years; hence in the very near future, these water mains will reach the end of their useful life and begin to degrade rapidly increasing the rate of water loss. Given that the current annual replacement rate of water mains in France is 0.6%, of which half is due to road works linked to urbanization, implies that the quality index could jump significantly in a very short term from the current 60%. This need of quality improvement illustrates the urgency of water main replacement. Our results show that in most cases a high water main quality index is cost efficient for the water utilities. However, we observe that regional differences have a large impact on the quality index. In particular, the differences in quantity demand, rural or urban regions and geographical differences in water abundance which impact the cost of water input. For example, the greater the quantity demand, the greater the pressure on water loss reduction; hence a larger optimal water main quality index. On the other hand, the cheaper the cost of water input, the lower the necessity to reduce water loss; hence a minimal quality index is obtained. Moreover, our results showed that the "cost recovery" initiative is a delicate issue. Depending on the initial conditions of the water utility, a high level of cost recovery may dampen quantity demand; offsetting water main quality improvement. Overall, our simple model provides important policy implications such as a possible implementation of a tax on water utilities which would incentivise them to reduce water loss under a certain threshold (15% for France), it also helps to compare the current water main quality to the theoretically (minimum) optimal level. Our next step is to develop this simple model into a dynamic framework; which is more appropriate to the case of water utility management. We will be able to deal with optimal water main *replacement* rates and integrate positive and negative externalities on the society over time.

6 Appendix

6.1 Appendix 1

The following is the comparative statics of the first order condition:

When the price of water input increases

$$\frac{d\overline{K}}{d\rho}=\frac{\alpha'_{\overline{K}}q\left(\overline{K}\right)+q'_{\overline{K}}\left(1-\alpha\left(\overline{K}\right)\right)}{\left(2(r-m)\left(1-\alpha\left(\overline{K}\right)\right)\alpha'_{\overline{K}}-\rho\alpha''_{\overline{K}}q\left(\overline{K}\right)-\rho q''_{\overline{K}}\left(1-\alpha\left(\overline{K}\right)\right)\right)}\geqslant 0$$

$$\frac{dW^{l}}{d\rho}=\frac{\alpha'_{\overline{K}}q\left(\overline{K}\right)}{\left(1-\alpha\left(\overline{K}\right)\right)}\left(1+\frac{\alpha\left(\overline{K}\right)}{\left(1-\alpha\left(\overline{K}\right)\right)}+\frac{\alpha\left(\overline{K}\right)q'_{\overline{K}}}{\alpha'_{\overline{K}}q\left(\overline{K}\right)}\right)\left(\frac{d\overline{K}}{d\rho}\right)\leqslant 0$$

When the cost of good quality mains increases:

$$\frac{d\overline{K}}{dr}=-\frac{\left(1-\alpha\left(\overline{K}\right)\right)^{2}}{\left(\rho q\left(\overline{K}\right)\alpha''_{\overline{K}_2}+q''_{\overline{K}}\left(1-\alpha\left(\overline{K}\right)\right)\rho-2(r-m)\left(1-\alpha\left(\overline{K}\right)\right)\alpha'_{\overline{K}}\right)}\leqslant 0$$

$$\frac{dW^{l}}{dr}=\frac{\alpha'_{\overline{K}}q\left(\overline{K}\right)}{\left(1-\alpha\left(\overline{K}\right)\right)}\left(1+\frac{\alpha\left(\overline{K}\right)}{\left(1-\alpha\left(\overline{K}\right)\right)}+\frac{\alpha\left(\overline{K}\right)q'_{\overline{K}}}{\alpha'_{\overline{K}}q\left(\overline{K}\right)}\right)\frac{d\overline{K}}{d\rho}\geqslant 0$$

In the case where quantity demanded is exogenous, the comparative static for an exogenous shift in quantity demanded is:

$$\frac{d\overline{K}_0}{d\overline{q}}=\frac{\alpha'_{\overline{K}_0}\rho}{\left(2(r-m)\left(1-\alpha\left(\overline{K}_0\right)\right)\alpha'_{\overline{K}_0}-\alpha''_{\overline{K}_0}\rho\overline{q}\right)}\geqslant 0$$

$$\frac{dW_0^{l}}{d\overline{q}}=\frac{\alpha\left(\overline{K}_0\right)}{\left(1-\alpha\left(\overline{K}_0\right)\right)}+\left[\frac{\alpha'_{\overline{K}_0}\overline{q}}{\left(1-\alpha\left(\overline{K}_0\right)\right)}+\frac{\alpha\left(\overline{K}_0\right)\overline{q}\alpha'_{\overline{K}_0}}{\left(1-\alpha\left(\overline{K}_0\right)\right)^{2}}\right]\frac{d\overline{K}_0}{d\overline{q}}$$

which is most likely negative.

6.2 Appendix 2

The first order condition implies

$$\rho q\left(\overline{K}\right)\alpha'_{\overline{K}}+\rho q'_{\overline{K}}\left(1-\alpha\left(\overline{K}\right)\right)+\left(1-\alpha\left(\overline{K}\right)\right)^{2}(r-m)=0$$

with

$$q\left(\overline{K}\right)=\frac{q_0}{\left(\left(\frac{(r-m)\overline{K}}{q_0}\right)\beta+\overline{p}\right)^{\theta}}$$

and

$$\alpha\left(\overline{K}\right)=\alpha_0\left(1-\frac{\overline{K}}{K}\right)$$

The derivative of the implicit function with respect to $\overline{K}$ and β gives

$$\left[\rho q\left(\overline{K}\right)\alpha''_{\overline{K}}+\rho q''_{\overline{K}}\left(1-\alpha\left(\overline{K}\right)\right)+2\left(1-\alpha\left(\overline{K}\right)\right)\alpha'_{\overline{K}}(r-m)\right]d\overline{K}+\left[\rho q'_{\beta}\alpha'_{\overline{K}}+\rho q''_{\overline{K}\beta}\left(1-\alpha\left(\overline{K}\right)\right)\right]d\beta=0$$

According to the functions we have specified, we have

$$\begin{aligned}
\alpha'_{\overline{K}} &= -\frac{\alpha_0}{K}<0\\
\alpha''_{\overline{K}} &= 0\\
q'_{\overline{K}} &= -\frac{\theta\left(r-m\right)\beta}{\left(\left(\frac{(r-m)\overline{K}}{q_0}\right)\beta+\overline{p}\right)^{\theta+1}}<0\\
q'_{\beta} &= -\frac{\theta(r-m)\overline{K}}{\left(\left(\frac{(r-m)\overline{K}}{q_0}\right)\beta+\overline{p}\right)^{\theta+1}}<0\\
q''_{\overline{K}} &= \frac{\theta\left(\theta+1\right)\left(r-m\right)\beta^2\left(\frac{(r-m)}{q_0}\right)}{\left(\left(\frac{(r-m)\overline{K}}{q_0}\right)\beta+\overline{p}\right)^{\theta+2}}>0\\
q''_{\overline{K}\beta} &= -\theta\left(r-m\right)\frac{\overline{p}-\theta\beta\left(\frac{(r-m)\overline{K}}{q_0}\right)}{\left(\left(\frac{(r-m)\overline{K}}{q_0}\right)\beta+\overline{p}\right)^{\theta+2}}>0\Longleftrightarrow\overline{K}>\frac{\overline{p}q_0}{\theta\beta(r-m)}
\end{aligned}$$

and

$$\frac{d\overline{K}}{d\beta} = -\frac{\rho q'_{\beta}\alpha'_{\overline{K}} + \rho q''_{\overline{K}\beta}\left(1-\alpha\left(\overline{K}\right)\right)}{\rho q''_{\overline{K}}\left(1-\alpha\left(\overline{K}\right)\right) + 2\left(1-\alpha\left(\overline{K}\right)\right)\alpha'_{\overline{K}}(r-m)}$$

The denominator is clearly positive while the numerator can be either positive or negative depending on the level of $\overline{K}$.

Finally the demand reaction is given by

$$\frac{dq}{d\beta} = \frac{\partial q}{\partial \beta} + \frac{\partial q}{\partial \overline{K}}\frac{\partial \overline{K}}{\partial \beta}$$

References

Arbués, F., Garcıa-Valiñas, M. Á., and Martınez-Espiñeira, R. (2003). Estimation of residential water demand: a state-of-the-art review. *The Journal of Socio-Economics*, 32(1):81–102.

AWWA (2012). Buried no longer: Confronting america's water infrastructure challenge. *American Water Works Association.*

Barraqué, B. (2009). Valuing water: the economics of an'impure public good'. *Water as a Catalyst for Change: Making the Passage through the XXIst Century-FLAD-Lisboa, 2005*, pages 191–232.

Berland, J.-M. and Juery, C. (2001). Etude sur la structure par âge des réseaux d'alimentation en eau potable et d'assainissement. Technical report, Office International de l'Eau.

Chong, E., Huet, F., Saussier, S., and Steiner, F. (2006). Public-private partnerships and prices: Evidence from water distribution in france. *Review of Industrial Organization*, 29(1-2):149–169.

Colbach, P. (2014). Amortissement des infrastructure d'eau.

Colombo, A. F. and Karney, B. W. (2002). Energy and costs of leaky pipes: Toward comprehensive picture. *Journal of Water Resources Planning and Management*, 128(6):441–450.

Elnaboulsi, J. C. (2009). An incentive water pricing policy for sustainable water use. *Environmental and Resource Economics*, 42(4):451–469.

EPA (2013). Water audits and water water loss control for public water systems. *United States Environmental Protection Agency*.

Feigenbaum, S. and Teeples, R. (1983). Public versus private water delivery: a hedonic cost approach. *The review of Economics and Statistics*, pages 672–678.

Folkman, S. (2012). Water main break rates in the usa and canada. *Utah State University*.

Garcia, S. and Thomas, A. (2001). The structure of municipal water supply costs: Application to a panel of french local communities. *Journal of Productivity Analysis*, 16(1):5–29.

Garcia, S. and Thomas, A. (2003). Regulation of public utilities under asymmetric information. *Environmental and Resource Economics*, 26(1):145–162.

Hansen, J. K. (2009). Optimal water-utility infrastructure investment: Testing effects of population, capital, and policy on the decision. *Working Paper, University of New Mexico*.

Majdouba, S. (2011). Le patrimoine des canalisations d'eau potable: Caracterisation, historique et pathologies. *AgroParisTech*.

Martins, R., Coelho, F., and Fortunato, A. (2012). Water losses and hydrographical regions influence on the cost structure of the portuguese water industry. *Journal of Productivity Analysis*, 38(1):81–94.

ONEMA (2012). Le prix de l'eau.

Pearson, D. and Trow, S. (2005). Calculating the economic levels of leakage. In *Leakage 2005 Conference Proceedings*.

Radisson, L. (2011). Eau et assainissement: rénover les réseaux et...augmenter la facture?

Rogers, P., Bhatia, R., and Huber, A. (1998). *Water as a social and economic good: How to put the principle into practice*. Global Water Partnership/Swedish International Development Cooperation Agency Stockholm, Sweden.

Salvetti, M. (2013). The network efficiency rate: a key performance indicator for water services asset management? *7th IWA International Conference on Efficient Use and Management of Water*.

Spiller, P. T. and Savedoff, W. (1999). Government opportunism and the provision of water. *Spilled Water: An Institutional Commitment to the Provision of Water Services, Washington, DC: InterAmerican Development Bank*.

Zschille, M. and Walter, M. (2010). Cost efficiency and economies of scale and density in german water distribution. Technical report, Working Paper. Berlin: German Institute for Economic Research (DIW).